Haptic Velocity Guidance System by Accelerator Pedal Force Control for Enhancing Eco-Driving Performance

Feilong Yin, Ryuzo Hayashi, Raksincharoensak Pongsathorn and Nagai Masao

Abstract This paper describes a haptic velocity guidance system with the purpose of realizing better fuel efficiency and enhancing road capacity by using information from Intelligent Transport Systems (ITS). By controlling the accelerator pedal reaction force, the proposed system provides a desired pedal stroke and guides the driver to achieve a desired velocity in real time. The effectiveness of the proposed haptic velocity guidance method is verified by experiments using Driving Simulator (DS). The comparison with the other guidance HMI is presented via experimental results. The experimental results show that the proposed haptic guidance, which provides high accuracy and quick response in velocity tracking, is a promising velocity guidance HMI.

Keywords Pedal force control · Haptic velocity guidance · Human–machine-interface

1 Introduction

Nowadays, the automobile is absolutely essential throughout the world. On the other side, fuel consumption and automobile carbon dioxide emission have become serious energy and environmental problems, respectively. To solve these problems, eco-driving and eco-traffic have received considerable attention in recent years.

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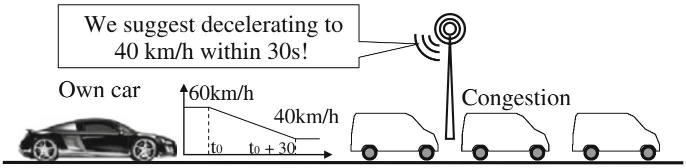

Fig. 1 Example of deceleration guidance application

Some devices based on eco-driving have been utilized in practice such as Eco-indicator of TOYOTA [1], Coaching and Teaching System of HONDA [2] and Eco-Pedal of NISSAN [3]. These systems reduce the consumption of fuel of each vehicle by restraining uneconomical acceleration, particular when the vehicle starts moving.

Another similar research is being developed by EU research project HAVEit. A bus applied the concept of "Active Green Driving" can use the right amount of energy according to the traffic environment and lower the fuel consumption with around 30 % compared with a traditional diesel engine [4].

However, this research focuses on eco-traffic guidance. As a future technology, management of traffic flows with ITS information is considered to realize the entire eco-traffic [5–8]. Figures 1 and 2 show the conceptual examples of the applications for such guidance. Figure 1 shows that the host vehicle saves fuel by starting deceleration gently ahead of traffic congestion out of sight. Figure 2 shows that a car is climbing up a slope. The driver may not notice the deceleration of own car which will cause traffic congestion. The velocity guidance system receives the warning and the suggestion of optimal speed from ITS infrastructure and guides the driver to recover the velocity quickly to avoid traffic jam. By conducting these, both fuel and time efficiencies can be improved significantly.

Traffic flow control requires highly accurate velocity guidance. Conventional velocity guidance methods include visual method such as indicators in instrument panel or on screen display of car navigation system and audio methods such as voice navigation by a speaker. In realization of accurate velocity guidance, visual methods have an advantage that it can show quantitative and continuous information as an indicator whereas an excessive gaze at the indicator may distract the driver's attention from ambient environment. On the other hand, frequent presentation of information may disturb the passengers' conversation or the enjoying of radio though audio methods do not distract the driver's attention from the environment so much. Since the haptic guidance has no such shortcomings, it is considered as the best way to accomplish velocity guidance.

In the aim of improving the fuel efficiency and traffic capacity, the authors propose a high accurate velocity guidance system. By changing the characteristics of the pedal reaction force, the proposed system informs the driver of the desired pedal stroke to realize an ideal velocity in real time. An experimental system is installed in the DS of Tokyo University of Agriculture and Technology (TUAT DS) (Fig. 3). The effectiveness of this velocity guidance system was presented in 22nd IAVSD.

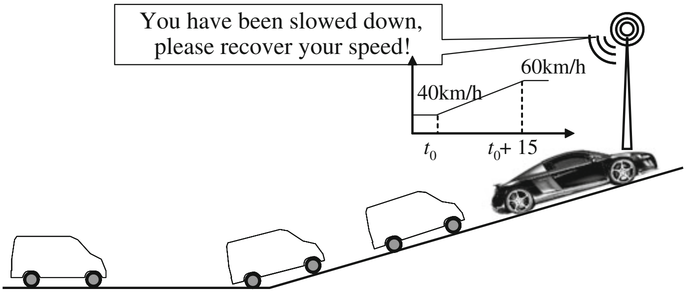

Fig. 2 Example of velocity recovering guidance application

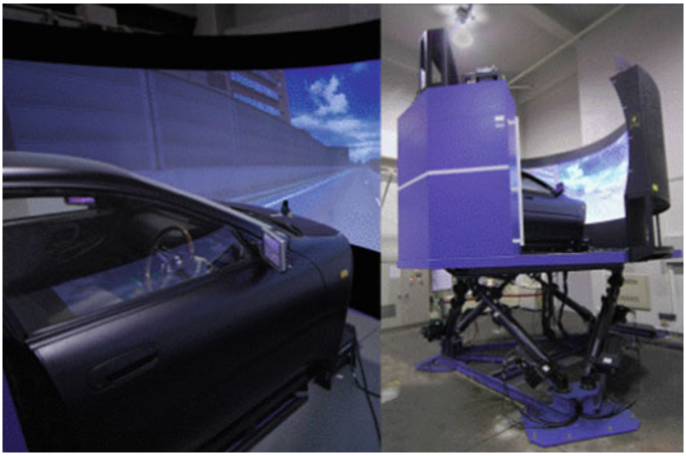

Fig. 3 TUAT driving simulator

2 Haptic Velocity Guidance System

The block diagram of haptic velocity guidance assistance system is shown in Fig. 4. This system has three basic functions: ITS information acquisition, desired pedal stroke calculation and desired pedal stroke guidance by haptic pedal.

3 Acquisition of its Information

The system gets ideal velocity profile from the ITS infrastructures for the guidance in the practical use. Since this research is carried out with a driving simulator and this paper intends to evaluate the proposed HMI, the accurate development of this function is not necessary. Accordingly, a desired (ideal) velocity profile based on typical driving is created to simulate this function.

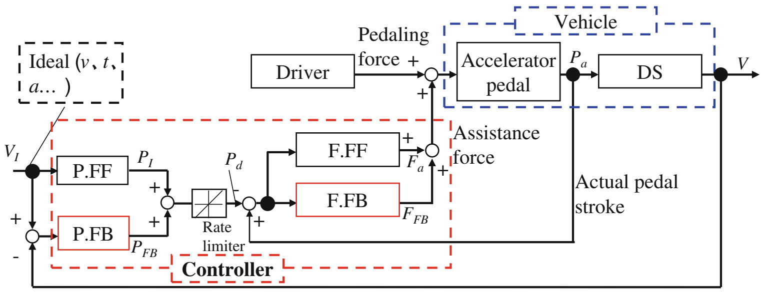

Fig. 4 Block diagram of haptic velocity guidance assistance system

4 Calculation of Desired Pedal Stroke

The desired pedal stroke (P_d) is calculated by two controllers: *Ideal Pedal Stroke Calculator* (P.FF) and *Velocity Error Feedback* (P.FB) controller.

The P.FF is a feed forward controller. P.FF is required to calculate the desired pedal stroke depending on the vehicle characteristics without considering the slope, wind, etc. However, a complex P.FF itself is a very tough research which needs a lot of time. In this paper, the ideal pedal stroke profile which realizes the ideal velocity profile is roughly calculated offline from the velocity response characteristic of the TUAT DS.

From previous experiments, it is found that the velocity error ($V_e = V - V_I$) mainly contains two parts, random error and steady state error that is caused by environmental variation, human delay or mistake, etc. Thus, a PI control described as follow is utilized in P.FB:

$$P_{FB} = \left(K_P + \frac{K_I}{s}\right) V_e \tag{1}$$

Here P_{FB} is the adjusting pedal stroke, K_P is the proportional gain, K_I is the integral gain and s indicates the Laplace operator. Since the feed back of velocity is mainly related to the vehicle driving performance, the optimal parameters of the P.FB are observed from DS simulation. By comparing the accuracy of the actual velocity and the degree of fluctuation of the pedal stroke, the optimal set is: $K_P = 3$ %(km/h) and the $K_I = 0.1$ %/s/(km/h).

5 Desired pedal Stroke Guidance by Haptic Pedal

The guidance will be accomplished by changing the reaction force of the haptic pedal. To realize the characteristics control of the pedal reaction force, an additional pedal reaction force generation mechanism is installed in the DS. The pedal is connected to an AC servomotor via mechanical linkages. A low inertia motor is

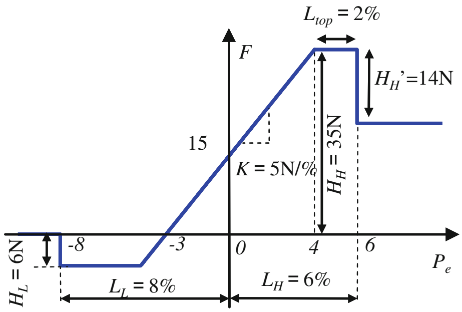

Fig. 5 Haptic pedal force characteristics with respect to the pedal stroke deviation

chosen and no gear transmission is used so that the additional mechanism does not obviously change the passive pedal characteristic. Additional reaction force with maximum value, i.e. 100 N could be generated by this mechanism.

The additional reaction force that guides the driver to desired pedal stroke is decided by two controllers: *Fixed Pedal Reaction Force Characteristic Controller* (F.FF), which is a feed forward controller, and *Pedal Stroke Error Feedback Controller* (F.FB), which is a feedback controller. The F.FF is designed according to the characteristics of passive reaction force and human stepping characteristics. The characteristic of F.FF is shown in Fig. 5 (the unit of pedal stroke is '%', varies from 0 to 100). Here horizontal axis indicates the pedal stroke error (P_e) which equals actual pedal stroke (P_a) minus desired pedal stroke (P_d), vertical axis indicates the additional reaction force of F.FF. There are two regions in additional reaction force: guidance region (pedal stroke error is from −8 to +6 %) and override region (pedal stroke error is over +6 % or under −8 %). The guidance region is designed to guide the driver to the desired pedal stroke by providing a click feeling when the driver passes the desired pedal stroke [9]. The balance of the stepping force, the passive pedal reaction force and additional reaction force is studied. Based on the study, the reaction force, where the actual pedal stroke equals to the desired pedal stroke, is designed to be 15 N and the largest additional reaction force is decided to be 35 N. From the previous experiment result, the drop force when the pedal stroke exceeds guidance region is decided to be −14 N.

F.FB is proportional to the integral of the pedal stroke error (P_e), and it is utilized to eliminate the steady state error of the pedal stroke.

$$F_{FB} = \frac{K_{P_e}}{s} P_e \tag{2}$$

An experiment to find the optimal K_{Pe} is carried out by three participants. By comparing the pedal stroke time history, the feedback of participants, K_{Pe} is decided to be 4 N/%.

The maximum guidance force that guides driver to release pedal is set to be 55 N and the maximum guidance force for guiding driver to step further is set to be −6 N. Such settings ensure that the guidance force could not operate the pedal itself.

Table 1 Participants information

NO.	Age	License history	Mileage/year (km)	Driving frequency
1	23	4	2,000	1/week
2	22	3	1,000	1/week
3	30	12	5,000	2,3/week
4	34	13	3,000	2,3/month
5	60	40	12,000	Everyday
6	62	43	9,000	4/week
7	23	3	100	4,5/year
8	23	3	0	0–1/year
9	33	14	800	1/month

6 Experiments for System Verification

An evaluation experiment to verify the accuracy of haptic velocity guidance by pedal reaction force control and compare with other types of guidance is carried out with TUAT DS. Questionnaires are done to learn the subjective feeling of the proposed system. The participants' information is shown in Table 1. Those are selected considering the variety of age and driving experience.

7 Guidance Technique

Four types of velocity guidance are used in this experiment: visual velocity guidance (V.visual), audio velocity guidance (V.audio), visual pedal stroke guidance (P.visual) and haptic pedal stroke guidance (P.haptic). A monitor is set in front of the instrument panel to achieve visual guidance (Fig. 6). The speaker of the TUAT DS is used to play the audio guidance and the haptic pedal mentioned above realizes the haptic guidance.

(a) *V.audio* The audio guidance contains the information of desired velocity and the time duration of adjustment. For example, if 'Please accelerate to 60 km/h in 15 s' is played and the actual velocity is 40 km/h, the driver should do his best to accelerate from 40 to 60 km/h with a constant acceleration around 0.37 m/s^2.
(b) *V.visual* (subgraph (b) of Fig. 6) The green bar indicates the actual velocity and the yellow bar indicates the current desired (ideal) velocity (subgraph (a) of Fig. 5). During the guidance, the driver is instructed to follow the yellow bar as well as possible.
(c) *P.visual* (subgraph (c) of Fig. 6) The green bar indicates the actual pedal stroke; the yellow bar indicates the desired pedal stroke (as shown in Fig. 4) including velocity error feedback.

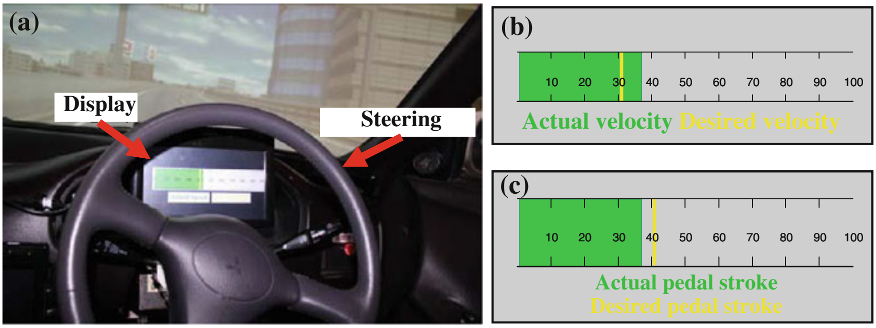

Fig. 6 Image of visual device

(d) *P.haptic* The haptic guidance guides the driver to the desired pedal stroke only by controlling the pedal reaction force. The meaning of the reaction force variation is explained to the participants as follow:

The force rises: the participant should further release the pedal.
The force decreases: the participants should further press the pedal.

8 Experiment Scenario

In order to simulate the real driving situation, Metropolitan Expressway of Tokyo which has many curves is selected to carry out this experiment. The primary task is to keep the lane as usual. The task performance will be examined by checking the maximum value of the lateral displacement. Here lateral displacement is the distance from the host car gravity center to the lane's center. The secondary task is to follow the guidance (velocity or pedal stroke). Training is executed before the experiment to make sure that every participant is familiar with the guidance methods. The ideal velocity profiles used in training and experiment are different.

9 Experimental Results

9.1 Lateral Displacement Comparison

The maximum value of lateral displacement is shown in Fig. 7, where the vertical axis indicates the displacement (m), horizontal axis indicates the guidance. The lines with different colors and marks indicate different drivers. The variety of displacements of every participant (except driver 2 and 7) is not obvious, almost in

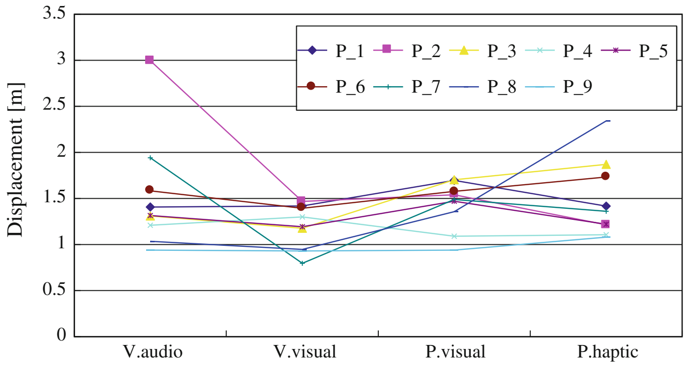

Fig. 7 Maximum value of the lateral displacement

the region of 1–2 m, which means that the participants accomplished the primary task very well. The ranges of the values are different from participant to participant caused by individual difference. The lateral displacement data shows that the result of this experiment is credible.

9.2 Velocity Comparison

As an example, velocity time histories of participant 3 are shown in Fig. 8. Here (a) is the result of audio velocity guidance (b) is the result of visual velocity guidance (c) is the result of visual pedal stroke guidance and (d) is the result of haptic pedal stroke guidance. The vertical axis indicates the velocity (km/h), horizontal axis indicates the time, the blue lines indicate desired velocity and the red lines indicate the actual velocity. The actual velocity of haptic guidance shows better accuracy, smoothness in following the desired value and the reaction time is shorter than visual guidance and audio guidance as well.

Instead of showing all the time history of all the participants, the RMS of velocity error of all experiments is shown in Fig. 9, where the vertical axis indicates the RMS (km/h), horizontal axis indicates the guidance. For all participants, the RMS of velocity error of haptic guidance is the smallest and nearly the same, which means haptic guidance suits this task very well.

9.3 Pedal Stroke Comparison

Pedal stroke guidance time histories of participant 3 are shown in Fig. 10. Here (c) is the result of visual pedal stroke guidance and (d) is the result of haptic pedal

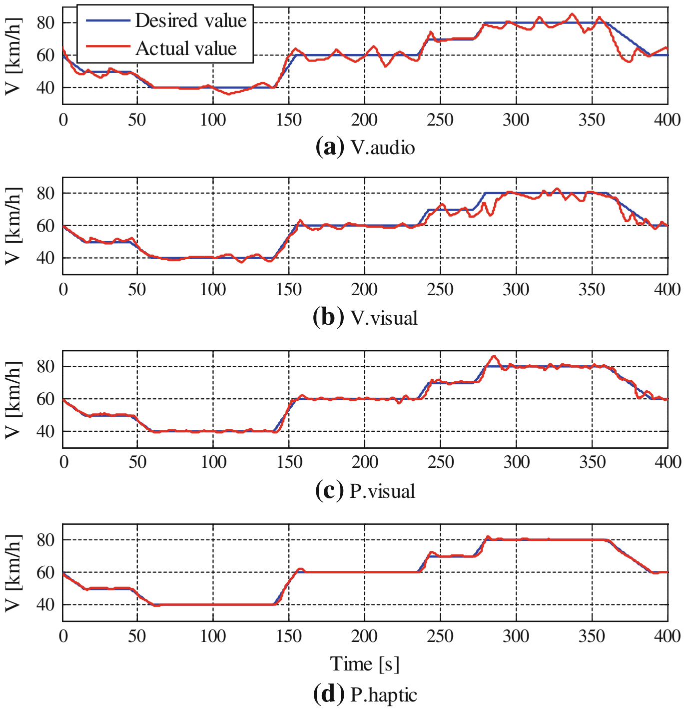

Fig. 8 Velocity time history of participant 3

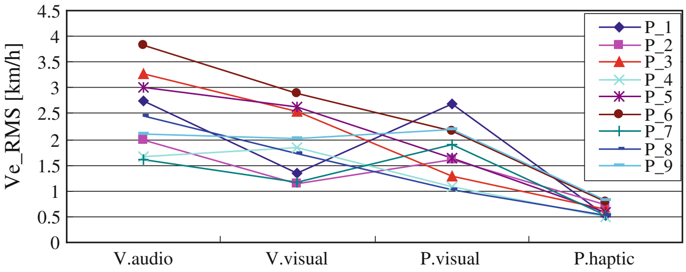

Fig. 9 RMS of velocity error of all guidance and all participants

stroke guidance. The vertical axis indicates the pedal stroke (%), horizontal axis indicates time; the blue lines indicate desired pedal stroke and the red lines indicate the actual pedal stroke. The desired pedal stroke of P.visual and P.haptic is the sum of ideal pedal stroke and adjusting pedal stroke. The result of haptic guidance is better than the result of visual pedal stroke guidance; it shows that the haptic guidance is easier to follow. The pedal stroke of haptic velocity guidance is smoother, which infers higher fuel efficiency (Fig. 11).

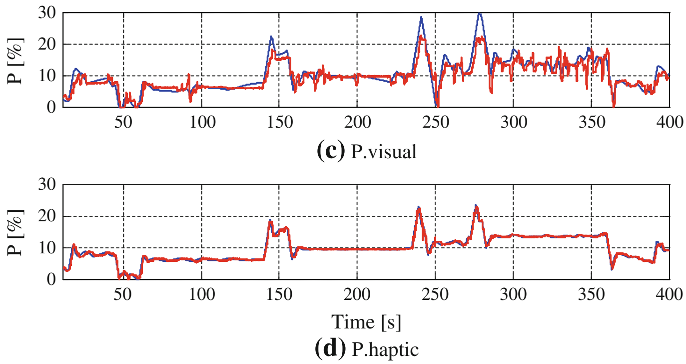

Fig. 10 Pedal stroke time history of participant 3

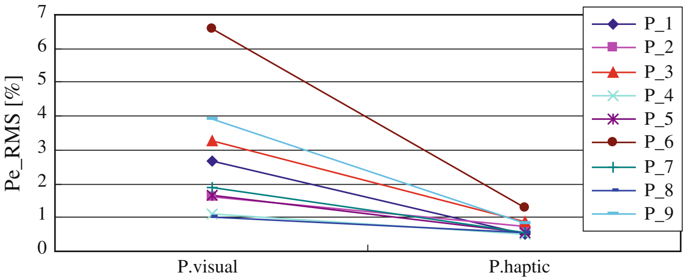

Fig. 11 RMS of pedal stroke error of pedal stroke guidance and all participants

During velocity guidance, the drivers are not required to follow the desired pedal stroke. Therefore only the RMS of pedal stroke error of *P.visual* and *P.haptic* is shown in Fig. 8. It can be seen that the accuracy of *P.haptic* of all participants are almost the same, and smaller than *P.visual.* It can be observed that the effect of haptic device is superior comparing with visual device from this experiment.

9.4 Pedal Stroke Tracking

Another experiment is arranged to study the driver's response during haptic guidance. An example of pedal stroke guidance is shown in Fig. 12. Subfigure (a) shows time history of desired pedal stroke P_d (in black) and time history of actual pedal stroke P_a (in blue). Subfigure (b) shows time history of guidance force F_a. The red line is the pedal stroke calculated by the driver-pedal model which will be described latter. The followings could be observed:

(a) The guidance force normally keeps constant while the desired pedal stroke is invariant.

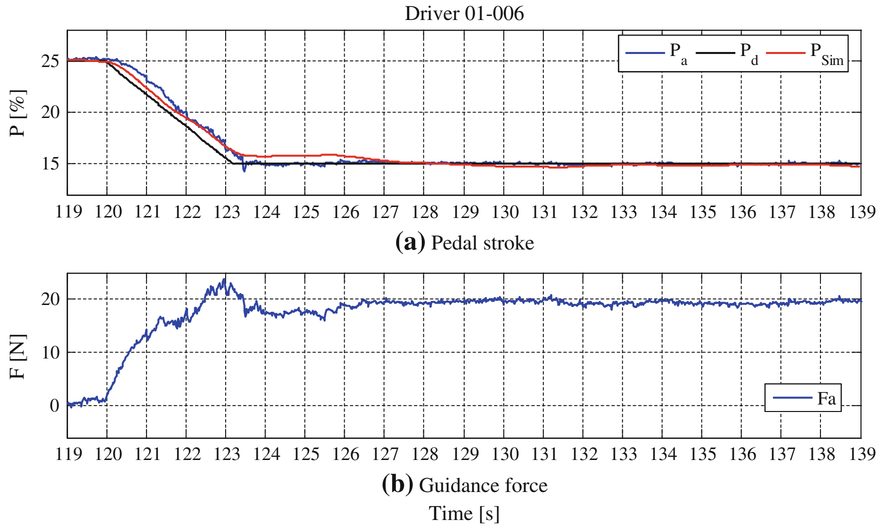

Fig. 12 Time history of pedal stroke guidance

(b) It can be noticed that drivers follow the desired pedal stroke with a little delay. Due to this the guidance force changed quickly right after the desired pedal stroke changed.
(c) The actual pedal stroke normally decreases when the guidance force increases (from 120 to 123 s). However, the actual pedal stroke keeps decreasing even the guidance force decreases after a period of increase (from 123 to 124 s).

Above all, it can be concluded that the pedal operation is related to the change of guidance force. In this paper, a model as expressed in Eq. 3 is employed to modify driver-pedal system. Here, driver is supposed to control pedal according to three values, the differential of guidance force ($\triangle F_a$), the integral of $\triangle F_a$ and the changing rate of $\triangle F_a$. Here, $\triangle F_a$ equals to recent guidance force deducts guidance force before desired pedal stroke changed. The gains are K_P, K_I and K_D, respectively. This model is called TPID model in this paper. The pedal stroke in time domain is described by Eq. 4. Here, $P_a(0)$ is the pedal stroke before the variation of desired pedal stroke and $F_a(0)$ is the guidance force before the start of desired pedal stroke changing.

$$G(s) = \left(K_P + K_I \frac{1}{s} + K_D s \right) e^{-\tau_L s} \tag{3}$$

$$P_a(t) = P_a(0) + K_P \Delta F_a(t - \tau_L) + \int_0^t K_I \Delta F_a(t - \tau_L) dt + K_D \frac{d\Delta F_a(t - \tau_L)}{dt},$$
$$\Delta F_a(t) = F_a(t) - F_a(0) \tag{4}$$

The parameters are identified by using least squares method. The data of guidance force is processed by a low pass filter and the threshold frequency is 5 Hz before calculating the rate of guidance force. The identified equation of Fig. 12 is:

$$G(s) = (-0.515 - 0.0014\frac{1}{s} + 0.00074s)\,e^{-1.081s} \tag{5}$$

The pedal stroke calculated by this equation is the red line in the Fig. 12a. From figure, it can be found that the simulated pedal stroke matched the actual pedal stroke very well and the mean absolute error of simulated pedal stroke is only 0.37 %. For most experimental data, there is a set of parameters that can give an accurate pedal stroke simulation result. Moreover, the K_I and K_D are always very small. This means that pedal stroke follows the haptic guidance mainly according to $\triangle F_a$ while time delay exists.

10 Conclusion

This paper proposes velocity guidance system by haptic interface-a haptic accelerator pedal. This system intends to realize better traffic efficiency by guiding the driver to drive with proper velocity. A haptic pedal is designed and the haptic guidance maneuver is discussed while the other functions are neglected or simply developed.

Four types of HMI are applied in the comparison experiments carried out with TUAT DS. The experimental results show that the drivers finished the lane keeping task with nearly the same accuracy. The haptic guidance method realized higher accurate velocity guidance than the other three. However, the comparison is not sufficient. In future research, comparison with other types of velocity assistance system, e.g. ACC, should be carried out as well.

A model is proposed that can accurately simulate the response of driver-pedal system. Since the friction exists in accelerator pedal, the modelling of pedal is complex. Moreover, human driver is in the loop, it is difficult to express haptic guidance only by using a simple model as proposed. The effort to find a more suitable model should be done in future research.

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